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GIS APPLICATION FOR NWS FLASH FLOOD GUIDANCE MODEL

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ABSTRACT

In response to a requirement for more uniform and consistent flash flood guidance procedures, the National Weather Service (NWS) with the assistance of the Iowa Institute of Hydraulic Research developed techniques for computing threshhold runoff for flash flood guidance. These techniques use a Geographic Information System (GIS) and Digital Elevation Models (DEM) to determine the required sub-basin boundaries and additional physical parameters for assessing threshold runoff values for 1-, 3-, and 6-hour rainfall durations. A rainfall-runoff model combined with an optional snow model computes the rainfall required to cause the threshold runoff responses. These procedures are being integrated with other NWS forecast office procedures. NWS expects to become operational with these procedures as part of the implementation of a modernized communication and distributed data processing system known as the Advanced Weather Interactive Processing System (AWIPS). The first field operations are expected to occur around the early part of 1994. The application of the GIS to determine the basin boundaries and the derivation of the various parameters for determining threshold runoff values are presented. The use of threshold runoff values with rainfall-runoff models to compute flash flood guidance is briefly described.

INTRODUCTION

This paper describes an objective method developed to compute threshold runoff values required in the computation of flash flood guidance at the NWS River Forecast Centers (RFC) (Sweeney, 1992). The method utilizes hydrologic and hydraulic principles, digital elevation model databases, and a geographical information sytem (GIS) applicable over the entire United States.

THRESHOLD RUNOFF THEORY

In the NWS, threshold runoff is defined as the runoff (in inches) from a rain of a specified duration that causes a stream to slightly exceed bankfull. When available, the flow at flood stage is used instead of slightly over bankfull. The method of determining threshold runoff value for a catchment is based on the threshold runoff value definition when it is assumed that the

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catchment responds linearly to rainfall excess (runoff), i.e., unit hydrograph theory applies. Since q_{pR} is the unit hydrograph discharge per unit area corresponding to unit volume of runoff of duration t_R, the peak discharge at the catchment outlet corresponding to a volume R of runoff of duration t_R is:

$$Q_p = q_{pR}RA \tag{1}$$

where Q_p is the peak discharge at the catchment outlet in cfs, A is the catchment area in mi^2, and R is the runoff amount in inches. Solving Eqn. (1) for R gives

$$R = \frac{Q_p}{q_{pR}A} \tag{2}$$

The problem is determining Q_p, q_{pR}, and A from observed field data that are expected to be available on a national basis. As a general guideline, utilization of GIS and national digital elevation databases allows the determination of geometrical catchment characteristics. Channel cross-sectional characteristics that determine Q_p cannot be resolved with present-day GIS databases and, if they exist at all, are the product of surveys limited in regional coverage. We present several options depending on data availability. A more detailed discussion of the theory is given in Sweeney (1992).

Bankfull Discharge

The value of Q_p can be determined by the use of Manning's formula for turbulent flow (Linsley, et al., 1982) to relate the runoff discharge to the channel geometrical and roughness characteristics for bankfull flow conditions. Bankfull discharge Q_p in cfs is given as a function of the local channel slope S_c in ft/ft, the hydraulic radius R_b in ft, and the channel bankfull cross-sectional area A_b in ft^2 by

$$Q_p = \frac{1.49 S_c^{0.5} R_b^{\frac{2}{3}} A_b}{n} \tag{3}$$

where n is Manning's roughness coefficient. After substituting a power function of local slope and hydraulic radius for Manning's n (Jarrett, 1985), and using D_bB_b for A, and then substituting hydraulic depth D_b expressed as $y_b/(m+1)$ for R_b, Eqn. (3) becomes

$$Q_p = 4.14 S_c^{0.13} \left(\frac{y_b}{m+1} \right)^{1.82} B_b \tag{4}$$

where y_b is the channel depth in ft at bankfull, m is the channel cross-section shape factor, and B_b is the bankfull width in ft.

Bankfull discharge can also be approximated by the two-year return period discharge Q_2 which is the discharge expected to be equalled or exceeded once every two years (Wolman and Leopold, 1957, pgs. 88-89). Q_p becomes Q_2:

$$Q_p = Q_2 \tag{5}$$

Typically, the return period of about 1.5 years is associated with bankfull discharge, but the values vary from about one to two years. The higher value of two years for the return period is chosen since more than bankfull flow is needed for flooding. For both cases, Manning's formula or return period, the data is limited and not available on a uniform basis over the U.S. The US Geological Survey (USGS) has compiled discharges for various return periods including the two-year return period (Jennings, 1992). Regionalization of the required parameters is necessary for each case in order to estimate their values in ungaged catchments from the values observed in a few gaged catchments in the region of analysis.

Peak Discharge

Snyder's synthetic unit hydrograph approach (Chow, et al., 1988, pg. 224-228) is a familiar method to determine the relationship between the effective rainfall of a given duration and peak runoff discharge q_{pR} and timing given geometric drainage basin characteristics as observed parameters.

$$q_{pR} = \frac{640C_p}{0.955t_p + 0.25t_R} \tag{6}$$

with

$$t_p = C_t \left[\frac{LL_c}{S^{0.5}}\right]^{0.38} \tag{7}$$

where C_p is a coefficient accounting for retention and storage with values typically in the range between 0.4 and 0.8 (Bras, 1990), t_p is the time to peak in hours, t_R is the duration in hours of the rainfall excess (duration of unit hydrograph), L is the main stream length in miles from the outflow point to the most distant basin boundary, L_c is the main stream length in mi from the outflow point to the basin centroid, S is the weighted channel slope in ft/mi, and C_t is a coefficient that takes the value of 0.35 for valley drainage areas, 0.72 for foothills, and 1.2 for mountainous areas (Linsley, et al., 1982).

Unfortunately, reasonable rainfall-discharge data to derive unit hydrographs are not available for most flash flood prone catchments. However, a more recent approach to deriving unit hydrographs based on the morphological structure of the channel network and channel cross-sectional data is being investigated (Rodriguez-Iturbe and Valdes, 1979).

APPLICATION OF THE GIS

The first consideration regarding the use of GIS is the available digital databases. The watershed program in the GIS GRASS (Geographic Resources Analysis Support System, CERL, 1991) determines watershed boundaries from a digital elevation model (DEM). Since nearly flat terrain complicates the process of locating boundaries, locations of known flat areas such as lakes and reservoirs are obtained from a Land Use, Land Cover (LULC) database. Elevations of streams in the DEM are lowered (or carved) by a fixed amount to better delineate the streams. Stream locations are obtained from the Environmental Protection Agency's (EPA) River Reach Files RF3. Some DEM data was initially obtained on 9-track tape from the USGS but is now available on

CD-ROMs from private vendors and from the Defense Mapping Agency (DMA). Likewise, some LULC data was initially obtained from the USGS and is now available on a CD-ROM from private vendors.
The digital databases are divided into USGS Hydrologic Cataloging Units (CU) and threshold runoff values are determined for each CU. The various steps for the GIS analysis are as follows:

LULC is scanned to determine the CUs within a given analysis window. A GRASS window is defined around each CU.

After defining the GRASS windows, the CU boundary vectors are converted to a GRASS cell file. Each DEM file falling within the GRASS window is converted into a cell file, too.

The EPA River Reach stream file for the CU inside the GRASS window is then converted to a cell file.

The various cell files are then overlayed to form a composite cell file. The analysis employs Universal Transverse Mercator (UTM) zones. The zone containing the major portion of the analysis area is made the zone of analysis. Files from the adjacent zone are converted into cell files with respect to the analysis zone. Considering the areal extent of a 1 degree by 1 degree DEM grid, no more than one zone crossing is expected for a particular analysis window.

Next, the mosaic is scanned for discontinuities across file boundaries. A cubic spline surface generation algorithm is used to mend these "seams".

Watershed analysis is then performed using the GRASS program R.WATERSHED (Ehlschlaeger, 1990). This program determines the network of streams in a certain analysis area and certain geometrical characteristics such as drainage area, stream length, and stream slope. The software package R.WATERSHED determines catchments by moving upward from the lowest elevation sections of the digital map. Land is given to the drainage basin which encroaches it first. When two basins meet, a ridge is formed. The travel uphill is done one contour line at a time. Digital data other than the elevation data (i.e., LULC) can be used to increase the accuracy of the procedure. Several tests of the procedure were made with 7.5 minute and 1 degree digital maps. In all cases R.WATERSHED correctly identified all basins and streams even in very flat areas. Only at the boundaries of the analysis maps the procedure failed. Such a problem is not expected when the CUs are used as described above. The scale of the minimum area considered to form a first order stream is set by the user (i.e., 5 km^2).

COMPUTING THRESHOLD RUNOFF

Using the program developed by Georgakakos, et al., (1991) called "thresR," threshold runoff values are computed for both stream branches that form each of the stream junctions determined by the GIS within the analysis area. An upper cut-off point is set for the largest drainage area for which a threshold runoff value is computed in order to be consistent with the assumptions of the unit hydrograph method used, i.e., uniform rainfall excess over the basin under study for a certain rainfall duration.

An upper cut-off is imposed since the larger scale streams and rivers contain forecast points for which the NWS RFCs routinely issue flood forecasts. However, sections of large drainage basins that drain into the downstream reaches of large streams and rivers are of interest since they can be prone to flooding from local rainfall over their tributary drainage basin. Such areas that have an identifiable stream draining as a tributary to the main stream or river would have been identified by the GIS for areas of moderate to high relief. Due to errors involved in the definition of the digital elevation data in very flat areas, a small draining stream of low order might not be identified. Such areas would create gaps in the map of the drainage basins with threshold runoff values assigned (assuming that the large stream or river would not have an associated threshold runoff value due to having too large of a drainage area), and some interpolation is needed to assign reasonable threshold runoff values in that vicinity. Such an issue should arise in the very flat areas of the Central U.S. in the downstream portions of large streams. A nominal value of 2,500 km^2 is used for the upper cut-off of areas for which a threshold runoff value is computed. Such a value corresponds to the scale of the smaller catchments for which the RFCs routinely issue site specific forecasts. It is also well within the scale of mesoscale convective complexes that cause flash flooding in the Central U.S.

An important input parameter is the minimum drainage area used to define the smallest streams. For compatibility with WSR-88D gridded data, the minimum area selected is 5 mi^2. The radar grid is approximately 6.25 mi^2 (16 km^2).

SUMMARY of ANALYSIS

Examples of 1-hour threshold runoff values are presented below for the Raccoon River catchment in Iowa, CU number 07100007. The threshold runoff values obtained are reclassed on an integer scale ranging from 2 to 254, and used for display with a gray scale color table. The final display gives the variation of threshold runoff values over the area of analysis. The catchment parameters have been produced using R.WATERSHED with a 5 km^2 minimum area. Theshold runoff values were computed for source areas up to approximately 50 km^2.

The threshold runoff values derived from Manning's equation for bankfull discharge and from Snyder's unit hydrograph are depicted in Figure 1 using a gray scale with dark shading implying low threshold runoff values and light shading implying high values. Each catchment was shaded based on its threshold runoff value. The values ranged between about 0.6 and 1.0 inches. Figure 2 depicts threshold runoff values derived from the two-year return period flow and Snyder's unit hydrograph. Values range from about 0.5 to 1.6 inches.

In all cases the variation in threshold runoff values is rather small for the area of analysis. Also, there is a rather smooth variation of values, with a few high values observed in small basins. The white areas adjacent to the main streams and rivers are areas with no threshold runoff values and interpolation using near-by values is needed in those cases.

DERIVATION OF FLASH FLOOD GUIDANCE

Flash flood guidance is the general term which refers to the average rainfall needed over an area during a specified period of time to initiate flooding on small streams in the area. Current moisture conditions and threshold runoff representing channel and basin characteristics described above are the major components of flash flood guidance. The Flash Flood Guidance System being developed in the NWS uses rainfall-runoff models with an optional snow model to determine the amount of rain necessary to produce an amount of runoff equal to the threshold runoff. This amount of rain is the flash flood guidance (Sweeney, 1992, pgs. 16-17). The process is repeated for each duration of rainfall and the corresponding threshold runoff for that duration. Flash flood guidance is computed for 1-, 3-, and 6-hour durations.

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Figure 1. Threshold runoff values for 1-hour rainfall duration based on Manning's equation at bankfull discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.6 (darkest color) to 1.0 inches. Raccoon River in Iowa, CU 07100007.

Figure 2. Threshold runoff values for 1-hour rainfall duration based on 2-year return period discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.5 (darkest color) to 1.6 inches. Raccoon River in Iowa, CU 07100007.